TABLE 22. QUENCH TOWER EMISSIONS VELOCITY DATA

| Location | Range (m/sec) | Average (m/sec) |
|---|---|---|
| Bairds and Scottish, Ltd. | 2.1-5.5 | a/ |
| Bethlehem, Tonawanda | 5.2-8.3 | 6.1 |
| Bethlehem, Lackawanna | 8.0-8.02 | 8.0 |
| Kaiser, 1972 | - | 6.4 |
| Kaiser, 1977 | 4.0-5.5 | a/ |
| Armco, Houston | 0.6-6.6 | 3.2 |
| DOFASCO | 2.0-4.1 | 3.1 |
| U.S.S. Lorain No. 1 | 7.0-12.3 | 9.4 |
| U.S.S. Lorain No. 2 | Not Available | - |

a/ Data insufficient to obtain average.

The other three sets of data for clean water tests pertain to rectangular towers using a typical quenching process. The value of 0.155 kg/Mg coke (0.31 lb/ton coke) for Kaiser is an average of three emissions tests, one of which was conducted when the baffles were severely eroded.[44-46] If we assume an average 50% efficiency for the baffles at Kaiser and DOFASCO, uncontrolled emissions would be in the range of 0.31 to 0.95 kg/Mg coke (0.62 to 1.9 lb/ton coke). If we assume 80 to 85% efficiency for three rows of baffles, uncontrolled emissions at Armco are estimated to be 0.8 to 1 kg/Mg coke (1.6 to 2 lb/ton coke). Based on these assumptions, uncontrolled emissions from a rectangular tower using a standard quenching process are probably in the range of 0.5 to 1 kg/Mg (1 to 2 lb/ton).

4.3.1.2 Effects of Water Quality on Emissions - Since a significant portion of the quench water is evaporated or entrained in the emissions stream as droplets, it is expected that the quality of the quenching water will have an effect on emissions. This obvious point is well supported by four sets of test results.

The most comprehensive analysis of the effects of water quality on emissions was conducted by Edlund, Laube, and Jeffrey using data from the first Lorain test. Edlund et al. have shown that for these tests, the total mass emissions are directly related to the amount of dissolved solids in the quench water. If the acetone probe wash (source of emissions unknown) and large diameter particles (probably caused by thermal fracturing of coke) are disregarded, the emission parameters showed an even greater dependence on water quality. Graphic results of these analyses are shown in Figures 22 and 23. Average emissions from the first set of tests at Lorain show a 57% reduction (1.79 to 0.78 kg/Mg) when the quench makeup was changed from process water to clean river water.[52]

Results from the second set of tests at Lorain are not yet complete. Hence, a comprehensive analysis of the effects of water quality on emissions is not possible. However, an analysis of total particulate emissions for both types of quench water shows that emissions averaged 1.19 kg/Mg coke (2.38 lb/ton coke) when process water was used as compared to 0.61 kg/Mg coke (1.22 lb/ton coke) when river water was used as makeup. This amounts to about a 50% reduction in emissions.[52]

Data from Bethlehem, Tonawanda also indicate a relationship between water quality and emissions. At the time of the tests, makeup water at Tonawanda was in part larry car scrubber effluent. Emissions from a rectangular tower with a single row of baffles were 0.49 kg/Mg coke (0.98 lb/ton coke).[47] This rate is two to three times higher than similar towers using clean water described in Section 4.3.1.1.

Finally, a series of tests was conducted at CF&I to compare emissions using industrial grade water and process water from the by-products plant as makeup water. While the grab sample technique and suspect velocity measurements make estimation of total emissions uncertain, it can be stated that grain loadings were one-third lower for industrial water than for process water.[49]

Based upon these data, it appears that the use of contaminated water for quench makeup can result in particulate emissions one and a half to three times greater than emissions from towers using clean water as makeup.

4.3.1.3 Effects of Coke Quality on Emissions - Little substantive information is available on the effects of coke properties on emissions. Those coke properties most likely to affect particulate emissions are temperature, greenness, and tendency of coke to fracture under thermal stress. Limited data are available on the relationship of temperature and greenness to emissions, but results are inconclusive. No data on the tendencies of certain coke to fracture were found.

Measurements of both oven temperature and coke greenness were available for almost all tests at U.S. Steel - Lorain and at DOFASCO. Analysis of these results, shown graphically in Figures 24 and 25, showed no relationship between emissions and these properties.

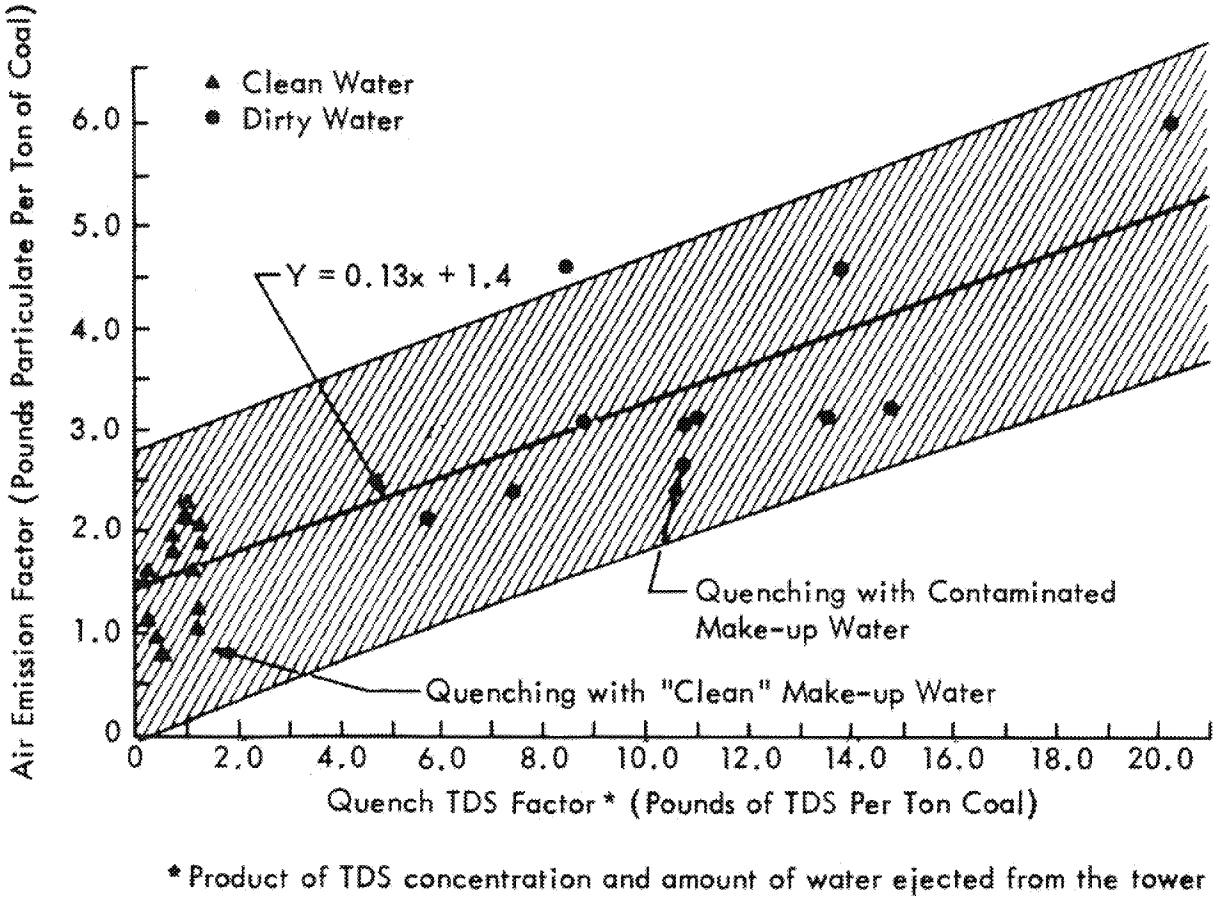


Figure 22. Total quench tower particulate emissions versus dissolved solids in quench water (95% confidence limits shown).

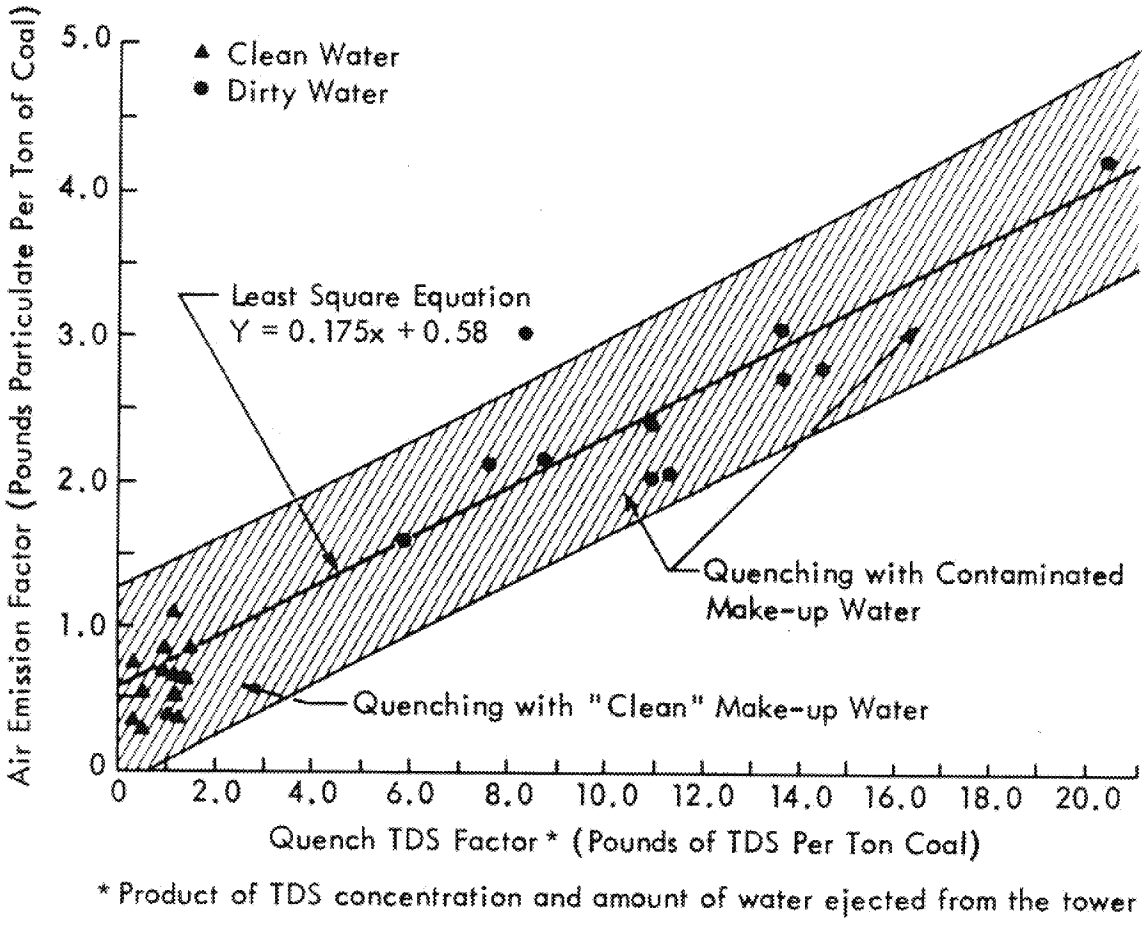


Figure 23. Total quench tower particulate emissions less acetone wash and filterable cyclone solids versus dissolved solids in quench water (95% confidence limits shown).

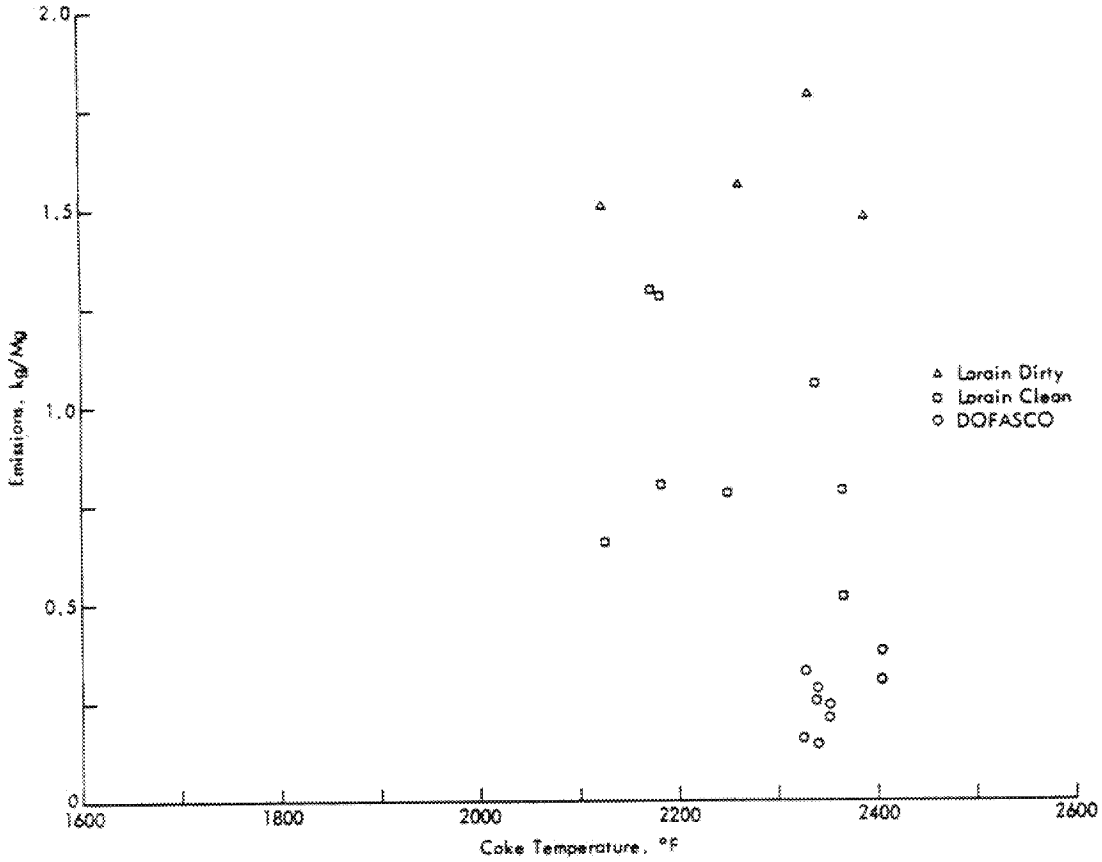


Figure 24. Correlation of emissions to coke temperature.

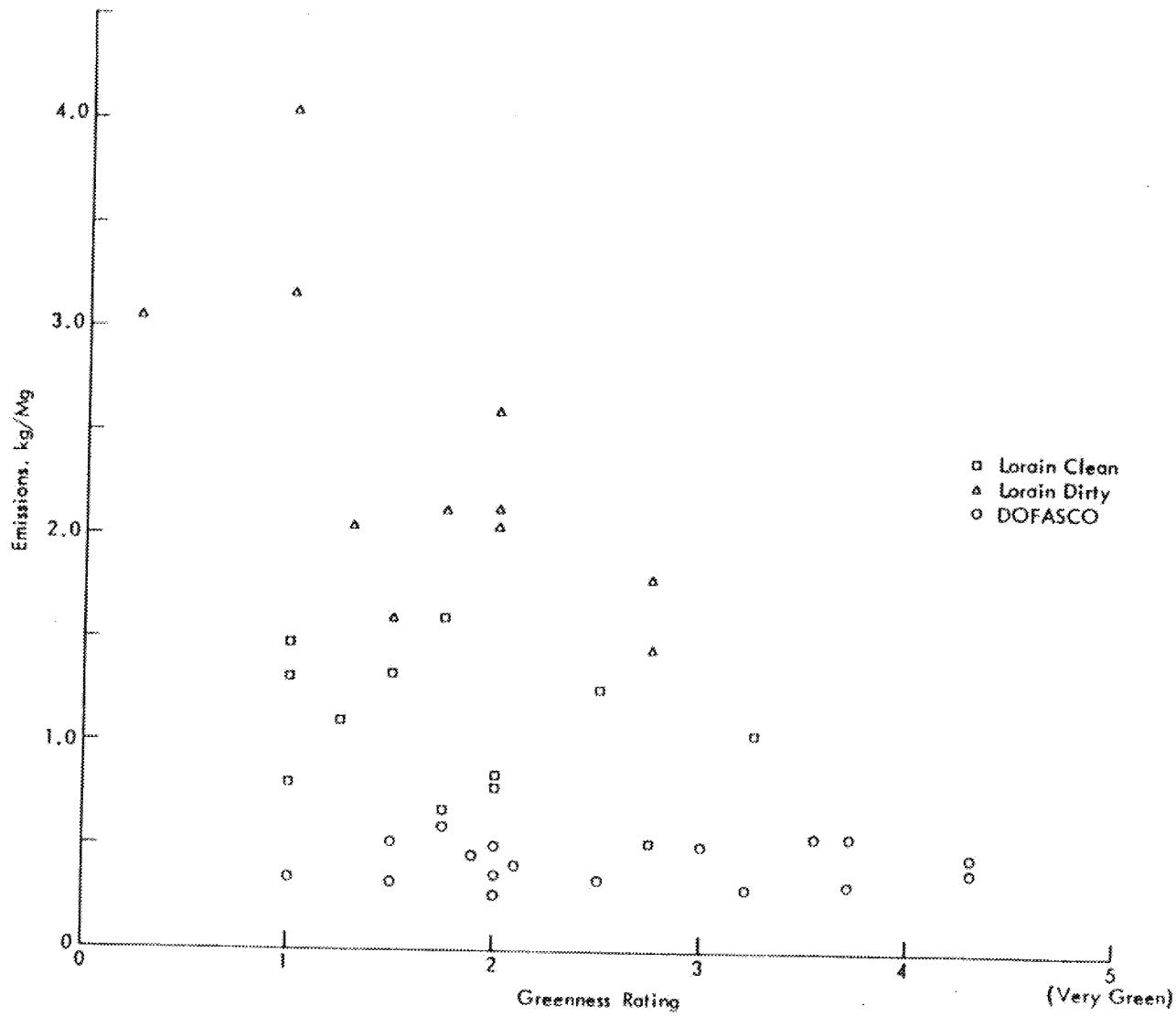


Figure 25. Correlation of emissions to coke greenness.

Jackson and Waple[38] conducted two test phases at Bairds and Scottish Steel, Ltd. During the first phase, coking time was 19-1/2 hr at a temperature of 1200°C (~2200°F). During the second phase, coking time had been extended to 35-1/2 hr with a reduction in temperature to 1100°C (~2000°F). Emissions in the uncontrolled tower declined from 6.95 kg per quench to 1.39 kg per quench, a reduction of 80%. However, data are insufficient to identify the effect of decrease in greenness or the specific effects of temperature decrease as opposed to increase in coking time.[38]

The results of the tests at Bethlehem are of some interest with regard to greenness of coke. At both Lackawanna and Tonawanda, grain loadings are higher in the outside sections of the tower than in the middle section. The end sections are above the part of the coke car containing the coke most likely to be green. However, data are insufficient to develop quantitative estimates.

Based on the above, it must be concluded that data are insufficient to determine the effects of coke quality on particulate emissions.

4.3.1.4 Particle Size Data - Data are insufficient to provide a highly quantitative analysis of emissions from quench towers. However, based on conversations with plant personnel and analyses of limited test data, it is possible to make the following statements: (a) emissions from nonbaffled quench towers contain significant quantities of large particles; and (b) emissions from baffled quench towers contain primarily fine particles.

This first statement is supported by statements of plant personnel. During telephone conversations and plant visits personnel frequently mentioned the amount of fallout before baffles were installed. Fullerton found that almost 2.7 kg of particles of size greater than 75 $\mu$m were emitted from an uncontrolled tower.[43] Finally, data from Bethlehem, Tonawanda indicate that in an uncontrolled tower 90% of the emissions were captured in the cyclone.[48] Most of these particulates are greater than 10 $\mu$m in diameter.

Three sets of emissions tests substantiate that particulate emissions from baffled towers are relatively small. Data from the first Lorain test indicate that for emissions from a tower using dirty makeup water, an average of 67% of the emissions were less than 10 $\mu$m in diameter.[52] For clean water makeup, an average of 82% of the emissions were less than 10 $\mu$m in diameter.[52] At DOFASCO an average of over 90% of the total particulate emissions were smaller than 10 $\mu$m in diameter.[51]

These results are supported by the Armco, Houston, tests. In an emissions stream from a quench tower with three layers of horizontal baffles, no discernible particulates were deposited in the probe or nozzle.[50] This indicates the absence of larger particles.

4.3.1.5 Total Particulate Emissions - Based upon the data presented above, it is estimated that emissions from an uncontrolled quench tower using clean makeup water are on the order of 0.5 to 1 kg/Mg coke (1 to 2 lb/ton of coke). The use of dirty makeup water or control device effluent as makeup will increase these emissions by a factor ranging from 1.5 to 3. Finally, baffling can eliminate from 50 to 90% of these emissions. Baffle efficiency is dependent upon baffle design and emissions stream characteristics.

4.3.2 Analysis of Organic Emissions Data

Limited data are available on organic emissions from quench towers. Available data generally fall into one of four types: (a) BaP; (b) total hydrocarbons; (c) phenols; and (d) benzene. Data for these organic emissions are presented in Table 23. In addition, preliminary PAH data are available from the second Lorain test. These are presented in Table 24. Analyses of each of these types of emissions are presented below.

4.3.2.1 BaP or Benzopyrene Emissions - The most extensive work on benzopyrene content of particulate emissions has been conducted by Masek of Czechoslovakia. A series of tests yielded an average benzopyrene content of 23.85 $\mu$g/g of particulate (i.e., about 0.0024% of total particulate emissions) for an unbaffled tower and 27.0 $\mu$g/g for a baffled tower. For particles of diameter less than 5 $\mu$m, Masek found benzopyrene levels of 56 $\mu$g/g for an unbaffled tower and a range from 37 to 91 $\mu$g/g for various baffling arrangements. This would indicate that higher levels of benzopyrene exist in fine particles than in large particles. Hence, baffling is less effective in controlling these emissions than in controlling total particulate emissions.

Data were also obtained by the State of New York on both Bethlehem Steel quench towers. At the Tonawanda plant, emissions varied from $0.163 \times 10^{-3}$ to about $0.511 \times 10^{-3}$ kg/Mg of coke at various parts of the tower. If we assume the larger value, BaP emissions are about 0.10% of total particulate emissions at Tonawanda (0.5 kg/Mg coke). This is for a tower without baffling using clean makeup water.

At Lackawanna, BaP emissions for two runs averaged $13.2 \times 10^{-6}$ kg/Mg of coke. This is equivalent to about 0.0027% of the total particulate catch at Lackawanna (0.49 kg/Mg). These results are for a baffled tower using larry car scrubber effluent as makeup.

It is worthy of note that the concentrations of BaP were higher at both ends of the car than in the middle. Since the coke at the ends of the oven (and hence the quench car) is cooler than that in the middle, it tends to be less carbonized (i.e., greener). Therefore, these results may suggest a relationship between greenness of coke and BaP emissions. However, data are insufficient to confirm such a conclusion.

# TABLE 23. ORGANIC EMISSIONS DATA

| Type of Emissions | Control comments/measures | Concentration | Emissions (kg/Mg) coke | % of particulate emissions |
|---|---|---|---|---|
| **Particulate Emissions** | | | | |
| Benzopyrene[a] | No control | - | $6.2 \times 10^{-6}$ | 0.0024 |
| | Baffles (2 rows 60° from horizontal) | - | $2.0 \times 10^{-6}$ | 0.0027 |
| Benzopyrene[b] | None | - | - | 0.002 |
| | Pressurized tower | - | - | 0.0012 |
| BaP[c] | No control/clean makeup | - | 0.163 - 0.511 $\times 10^{-3}$ | 0.033 - 0.10 |
| BaP[d] | Baffles/dirty makeup | - | $13.2 \times 10^{-6}$ | 0.0027 |
| BaP[e] | Baffles/clean makeup | 77 - 134 $\mu g/m^3$ | 0.113 - 0.229 $\times 10^{-3}$ | 0.019 - 0.038 |
| | Baffles/dirty makeup | 305 $\mu g/m^3$ | $0.462 \times 10^{-3}$ | 0.039 |
| **Gaseous Emissions** | | | | |
| Total Hydrocarbons[c] | Clean water | - | 0.0084 | - |
| Total Hydrocarbons[d] | Dirty makeup | - | 0.085 | - |
| Total Hydrocarbons[f] | Clean water | 600 ppm | - | - |
| | Contaminated water | 3,000 ppm | - | - |
| Total Organics[g] | Clean water | 3,400 $mg/m^3$ | 5.425 | - |
| | Dirty water | 403.5 $mg/m^3$ | 0.7215 | - |
| Aliphatic Hydrocarbons | Clean water | 734.7 $mg/m^3$ | 1.172 | - |
| | Dirty water | 14.29 $mg/m^3$ | 0.026 | - |
| Aromatic Hydrocarbons | Clean water | None detected | - | - |
| | Dirty water | None detected | - | - |
| Nonaromatic Heterocarbons | Clean water | None detected | - | - |
| Aromatic Heterocarbons | Dirty water | 1.64 $mg/m^3$ | 0.003 | - |
| | Clean water | 2,409 $mg/m^3$ | 3.842 | - |
| | Dirty water | 259.2 $mg/m^3$ | 0.464 | - |
| Aldehydes, Esters Carboxalic Acids, Acrylate Polymers | Clean water | 22.8 $mg/m^3$ | 0.340 | - |
| | Dirty water | 95.61 $mg/m^3$ | 0.171 | - |
| Keytones, Amine Salts Phosphines, Isocyanate | Clean water | 44.70 $mg/m^3$ | 0.0715 | - |
| | Dirty water | 32.80 $mg/m^3$ | 0.0585 | - |
| Total Hydrocarbons[h] | No data | 8.54 ppm | - | - |
| | | 17.37 ppm | - | - |
| Phenols[i] | Dirty makeup | - | 0.158 | - |
| Phenols[j] | Water treated for phenol removal | - | 24.0 | - |
| Phenolic Compounds[k] | Clean makeup | 14 ppm | - | - |
| Phenols[c] | Clean makeup | - | 0.003 | |
| Phenols[d] | Dirty makeup | - | 0.093 | |
| Phenols[f] | Clean makeup | ND | - | - |
| Benzene[h] | Water source uncertain | 0.005 ppm | - | - |
| | | 0.040 ppm | - | - |

a/ Tests by V. Masek reported in Staub (Reference 41).
b/ Tests by V. Masek reported in BCRA 153 (Reference 42).
c/ Tests at Bethlehem, Tonawanda (Reference 47).
d/ Tests at Bethlehem, Lackawanna (Reference 48).
e/ Second set of tests at U.S.S. Lorain (Reference 52).
f/ Grab samples from CF and I (Reference 49).
g/ First set of tests at U.S.S. Lorain (Reference 52).
h/ Two grab samples at second U.S.S. Lorain test (Reference 52).
i/ Polish test data, sample method unknown (Reference 40).
j/ U.N. data from the USSR (Reference 40).
k/ Kaiser Steel Data (Reference 44-46).

TABLE 24. PRELIMINARY PAH RESULTS FOR SECOND SERIES OF LORAIN TESTS

| Species | Test No. 5[a] Conc. $\mu g/m^3$ | Test No. 5[a] Emissions g/Mg | Test No. 7[a] Conc. $\mu g/m^3$ | Test No. 7[a] Emissions g/Mg | Test No. 14[b] Conc. $\mu g/m^3$ | Test No. 14[b] Emissions g/Mg |
|---|---|---|---|---|---|---|
| Indene | ND | 0.216 | ND | - | 69 | 0.121 |
| Naphthalene | 173 | 0.005 | 99 | 0.116 | > 6,846 | > 12.0 |
| Benzothiophene | 4.2 | 0.005 | 2.3 | 0.0027 | 937 | 1.64 |
| Methyl Naphthalenes | 82 | 0.102 | 25 | 0.030 | 1,631 | 2.87 |
| Acenaphthylene/ Biphenylene | 31 | 0.040 | 11 | 0.013 | 1,892 | 3.32 |
| Biphenyl | 10.9 | 0.014 | 6.8 | 0.0080 | 345 | 0.60 |
| Dimethyl Naphthalenes | 135 | 0.169 | 25 | 0.029 | 352 | 0.615 |
| Fluorene | 70 | 0.087 | 35 | 0.042 | 2,190 | 3.85 |
| Carbazole | ND | - | ND | - | 470 | 0.820 |
| Debenzofuran/ methyl biphenyl | 69 | 0.0875 | 18 | 0.022 | 1,274 | 2.23 |
| Anthracene/ phenanthrene | 478 | 0.595 | 260 | 0.305 | > 4,005 | > 7.05 |
| Dibenzothiophene | 10 | 0.014 | 16 | 0.018 | 219 | 0.358 |
| Methyl anthracenes | 183 | 0.230 | 85 | 0.100 | 410 | 0.72 |
| Fluoranthene | 44 | 0.0545 | 31 | 0.036 | 918 | 1.65 |
| Pyrene | 38 | 0.048 | 25 | 0.034 | 737 | 1.29 |
| $C_{16}H_{12}$ PAH | ND | - | ND | - | 46 | 0.0815 |
| $C_{16}H_{12}$ PAH | ND | - | ND | - | 12 | 0.020 |
| $C_{16}H_{12}$ PAH | ND | - | ND | - | ND | - |
| $C_{16}H_{12}$ PAH | ND | - | ND | - | 11 | 0.020 |
| Methyl Fluoranthene | - | - | - | - | - | - |
| Methyl Pyrene | 20 | 0.026 | 13 | 0.016 | 120 | 0.211 |
| Dihydrobenzofluorene | ND | - | ND | - | 42 | 0.072 |
| Chrysene/Benz(a) anthracenes | 11.4 | 0.014 | 89 | 0.104 | 88 | 0.155 |
| Naphthobenzothiophene | ND | - | ND | - | 2.3 | 0.0040 |
| Methyl-chrysense | ND | - | ND | - | 14 | 0.0242 |
| Benzofluoranthene, benzo(e)anthracene | - | - | - | - | - | - |
| Benzo(a)pyrene | ND | - | ND | - | 118 | 0.208 |
| Perylene | 84 | 0.105 | ND | - | 76 | 0.133 |
| p-phenyl anthracene (IS) | ND | - | ND | - | ND | - |

(continued)

TABLE 24. (continued)

| Species | Test No. 5[a] Conc. $\mu g/m^3$ | Test No. 5[a] Emissions g/Mg | Test No. 7[a] Conc. $\mu g/m^3$ | Test No. 7[a] Emissions g/Mg | Test No. 14[b] Conc. $\mu g/m^3$ | Test No. 14[b] Emissions g/Mg |
|---|---|---|---|---|---|---|
| 7.12 Dimethyl Benz(a)anthracene | ND | - | ND | - | ND | - |
| Methyl-benzo pyrenes | ND | - | ND | - | ND | - |
| Dibenzo (c,g) carbazole | ND | - | ND | - | ND | - |
| 3-methyl cholanthrene | ND | - | ND | - | ND | - |
| Indeno (1,2,3-cd)pyrene | ND | - | ND | - | ND | - |
| Benzo (ghi) perylene | ND | - | ND | - | ND | - |
| Dibenzo (a,h)anthracene | ND | - | ND | - | ND | - |
| Coronene | ND | - | ND | - | ND | - |
| Dibenzo (ai and ah)pyrenes | ND | - | ND | - | ND | - |
| TOTAL | 1,443 | 1,802 | 745 | 0.875 | 22,844 | 39.9 |

ND = Not detected. Detection limit is $\frac{0.1 \text{ na}}{\mu \ell}$.

a/ Clean water test.

b/ Dirty water test.

The only other BaP results are a part of the preliminary test data from Lorain. BaP emissions were detected in the clean water makeup tests ranging from nondetected to $0.392 \times 10^{-3}$ kg/Mg. BaP levels averaging $0.462 \times 10^{-3}$ kg/Mg of coke were obtained during the dirty water tests. This again amounts to about 0.039% of the particulate emissions at Lorain for those tests. In addition, the Lorain data indicate that 25 to 60% of the BaP may be in gaseous form.

Thus, we believe the most reliable estimate of BaP emissions to be in the range of $0.15$ to $0.50 \times 10^{-3}$ kg/Mg.

4.3.2.2 Total Gaseous Hydrocarbon Emissions - Total gaseous hydrocarbon emissions data are extremely limited. Average emission rates of heavy hydrocarbons from Polish steel mills have been estimated at 0.098 kg/Mg coke. Test methodology was not described.

The State of New York measured gaseous hydrocarbons at Bethlehem, Tonawanda and Bethlehem, Lackawanna. The tests for hydrocarbons at Tonawanda (an unbaffled tower using clean makeup water) were determined to be 0.085 kg/Mg (Table 23).

The Lackawanna tower is baffled, but makeup water was larry car scrubber effluent. Average hydrocarbon emissions from the three runs were 0.0084 kg/Mg with the highest emissions levels being 0.015 kg/Mg. It is unexpected that hydrocarbon levels for the "dirty" water are lower than those from the clean water quenches.

Samples were taken to determine total gaseous hydrocarbon concentrations at CF&I, and also at the second series of tests at U.S. Steel - Lorain. At CF&I the concentration was reduced from 3,000 to 600 ppm by changing from process water to industrial water for makeup. At Lorain, hydrocarbon levels were 17.37 and 8.54 ppm for two tests with clean water. These two plants obviously have extremely different concentrations. Reasons for such a difference are not apparent.

Finally, total hydrocarbon emissions were determined during the first Lorain tests using a continuous sampling train with a polymer compound in a cooled absorber trap. Two tests were run using clean water makeup and one was conducted using contaminated water. As can be seen from Table 25, total organic emissions were 0.772 kg/Mg for the contaminated water tests and 5.425 kg/Mg for clean water tests. It should be noted that, unexpectedly, emissions were much higher for the clean water tests than for the dirty water test. However, investigation of these test results revealed that they are probably in error, due to contamination from the sampling train.

4.3.2.3 Phenol Emissions - Based upon the nature of coke oven gases and by-products wastewater, it is likely that the quench tower plume will contain some phenolic compounds. The results of several tests of phenolic content of quench tower emissions are analyzed below.

TABLE 25. HYDROCARBON DATA FROM LORAIN TEST NO. 1

| Type of organic compound | Contaminated water | | Clean water | |
|---|---|---|---|---|
| | $mg/m^3$ | kg/Mg | $mg/m^3$ | kg/Mg |
| Aliphatic hydrocarbons | 14.29 | 0.026 | 734.72 | 1.172 |
| Aromatic hydrocarbons | ND | ND | NA | NA |
| Non-aromatic heterocarbons (esters, alcohols) | 1.64 | 0.003 | ND | ND |
| Aromatic heterocarbons (phenols, nitrites, phthalate, esters) | 259.15 | 0.464 | 2,408.57 | 3.842 |
| Aldehydes, esters, carboxilic acids, acrylate polymers | 95.61 | 0.171 | 212.76 | 0.340 |
| Keytones, amine salts, phosphines, isocyanate | 32.80 | 0.0585 | 44.70 | 0.0715 |
| Totals | 403.49 | 0.7715 | 3,400.75 | 5.425 |

ND = Not Detected

NA = Detected but weight attributable to this compound not available.

The United Nations document on coke quenching reported the results of tests on a Polish quench tower using wastewater as makeup. Phenol emissions were reported as 0.158 kg/Mg coke produced. The test methodology was not described. The same document reported phenol emissions of 0.024 kg/Mg at a plant in the USSR where wastewater was treated for phenol removal.

Gaseous phenol emissions were analyzed for both Bethlehem towers by the State of New York. At Tonawanda, phenol emissions were reported to be 0.0015 kg/Mg (0.003 lb/ton). At Lackawanna, where scrubber effluent is used as makeup, three tests resulted in average phenol emissions of 0.093 kg/Mg with a range of 0.056 to 0.122 kg/Mg. Since this source has some particulate control, the results are not directly comparable. However, it can be seen that the emissions from the Lackawanna baffled tower, using some dirty makeup water, are about 30 times higher than the phenol emissions at the Tonawanda unbaffled tower using clean water.

Finally, grab samples were taken at CF&I to analyze the difference between process water and clean water as makeup. When process water was used, phenol levels of 450 to 550 ppm were detected. No phenols were detected when clean water was used.

Hence, most data appear to indicate that phenolic emissions are significantly higher when contaminated water is used as makeup.

4.3.2.4 Benzene Emissions - The only reported tests for benzene emissions were conducted during the second series of tests at Lorain. Two grab samples yielded concentrations of 0.040 and 0.005 ppm. Data are insufficient to permit any analysis of these results.

that in a quench tower. Collection by momentum forces relies on producing a sudden change of direction in the gas stream. The larger particles, because of their inertia, will continue to move in the same direction as the initial gas flow and are thus separated from the gas stream. Small particles will follow the streamlines and must be removed by other types of collection forces.

Particles carried in an upward flowing gas stream will, of course, tend to fall back down the tower unless they are of such a small size that the drag of the upward flowing gas stream exceeds the terminal settling velocity of the particle due to gravity. Test data discussed earlier showed that gas velocities in quench towers are generally greater than 3 m/sec, which is great enough to suspend particles on the order of 1,000 m. Thus, it can be seen that only the very large particles would settle back into a quench tower against the opposing upward movement of gas.

Bends in the tower leading to the baffle section (i.e., offset tower) act as impingment surfaces and some particle collection may occur at these locations. When a gas stream carrying particulate matter impinges on a body, the gas is deflected around the body while the larger particles, because of their greater inertia, tend to strike the body and be collected on its surface.

The effectiveness of inertial impaction for particle collection is a function of the inertial impaction parameter which arises out of the force balance equations of fluid resistance opposing the motion of the particle. The inertial impaction parameter (dimensionless) is defined as:

$$N_I = \frac{C\ U_g\ \rho_p\ d_p^2}{18\ \mu_g\ d_c} \qquad (5.1)$$

where $C$ = Cunningham correction factor

$U_g$ = gas velocity, cm/sec

$\mu_g$ = gas viscosity, g/cm sec

$d_p$ = particle diameter, $\mu$m

$d_c$ = diameter of collecting body, cm

$\rho_p$ = particle density, g/cm$^3$

Ranz, Wong, and Johnstone[54] and other investigators have shown that the collection efficiency of inertial impaction is a function of the impaction parameter and that the impaction parameter ($N_I$) must exceed four in order for collection efficiencies to exceed 90%. Substitution of representative values of the gas velocity in quench towers into the above equation, indicates that particle

## 5.0 THEORETICAL ANALYSIS OF PARTICULATE REMOVAL IN QUENCH TOWERS

A previous section of this report showed that there are many variations in general tower designs, which could affect emissions. This included various tower configurations (straight or offset) and use of various baffle designs and baffle locations (being either near the top or bottom of the tower). However, the available test data were not sufficient to quantitatively assess the effect of these variations on emissions. A theoretical analysis was done in an attempt to develop a tool that might be useful in evaluating emissions from quench towers and the effectiveness of various baffle designs. The following subsections present this analysis, which is directed only to particulate emissions (particles or droplets) rather than to any emissions that may be partly or wholly in gaseous form (POMs or benzene).

### 5.1 PARTICULATE COLLECTION IN BAFFLE TOWERS

Several collection mechanisms or forces may act to achieve overall particulate collection in baffle towers used in coke quenching applications. Mechanisms which may be involved include gravity and momentum forces, centrifugal force, inertial impaction, and flux forces. The portion of the tower prior to any baffle section may act as a settling chamber and some growth and/or agglomeration of fine particulates may occur by condensation processes. However, the major particle collection is believed to occur in the baffle section. Each part of the tower is discussed separately in the following subsections.

#### 5.1.1 Particulate Removal Prior to Baffle Section

Particulate removal by gravity and momentum forces and particle growth via agglomeration and/or condensation processes may occur in the tower prior to the baffle section. The conditions of the gas stream and the configuration of the tower will dictate which processes may occur and their effectiveness.

5.1.1.1 Particulate Removal by Gravity and Momentum Forces - Particulate removal by these forces is mainly restricted to coarse particles.* The simplest method of removing particles from a moving gas stream is to allow them to settle out under the force of gravity. Large particles will often do so if their settling velocity is greater than that of an upward flowing gas stream like

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* For the sake of convenience, the standard definition of coarse particles is used and refers to particles greater than 76 $\mu$m.

removal would be minimal, primarily because a value for $d_c$ would be large. Thus, general towers of offset design are not likely to much affect emissions, except perhaps for very large particles (> 1,000 $\mu$m).

5.1.1.2 Particle Agglomeration and/or Growth - Various particle agglomeration or growth mechanisms may occur in the portion of the tower prior to the baffle section which might enhance overall particulate collection. The conditions of the gas stream such as vapor pressure, grain loading, particle size distribution, velocity, etc., will determine which mechanisms are operative and their net effect.

The agglomeration and growth mechanisms are most effective in the fine particle size range (< 3 $\mu$). This point is illustrated by consideration of particle growth by condensation.* Calvert[55] cites the following equation for particle growth rate by condensation.

$$r_p \frac{dr_p}{dt} = \frac{M\ D}{\rho_L\ R\ T} (p_o - p_\infty) \left[\frac{1}{\frac{D}{r_p\ \nu\ \alpha} + 1}\right] \qquad (5.2)$$

where $\alpha$ = condensation coefficient, dimensionless

$\nu = (R \cdot T/2 \cdot M)^{1/2}$

M = molecular weight, g/gmol

D = diffusivity, $cm^2/sec$

$\rho_L$ = density, $g/cm^3$

R = gas constant

T = absolute temperature, $^\circ K$

$p_o$ = vapor partial pressure at drop surface, $g/cm^2$

$p_\infty$ = vapor pressure in air stream, $g/cm^2$

$r_p$ = particle radius, cm

* Condensation is selected for discussion because the use of water in the quench process makes this mechanism a strong possibility in quench towers.

Equation (5.2) indicates that the rate of particle growth varies inversely with particle radius. Experimental data such as those shown in Figure 26, also show that an aerosol grows at a rate roughly proportional to the inverse of its radius. Growth continues until the ambient vapor pressure is lowered to equilibrium due to condensation of the available water vapor or due to particle movement to different regions. The data in Figure 26 were reported by Calvert and Gandhi[56] as part of their work on flux force/ condensation scrubbing in a pilot-scale sieve plate column system. In Figure 26

$d_{pg}$ = dry mass median particle diameter

$G_g = 2.5$ = geometric standard deviation of particle size distribution

$n_p$ = particle number density

$q'$ = condensation ratio $\frac{\text{g water condensed}}{\text{g dry gas}}$

$f_p$ = particle condensation ratio

In summary, while particle agglomeration and growth may occur in the tower prior to the baffle section, the processes will be mostly confined in their effectiveness to the fine particle regime (i.e., $< 5\ \mu m$) and growth by condensation is minimal for particles larger than 5 m. The degree to which these processes contribute to the overall control of particulate emissions in quench towers is probably quite small because the baffle section, which serves as the final collection point, is a very inefficient device for fine particle collection. This point is illustrated in the discussion of baffle performance which is presented next.

### 5.1.2 Particulate Removal by Baffles

The major site of particulate removal in the quench towers is the baffle section. Recent work by Calvert et al.[57] has resulted in the development of a mathematical model which predicts the collection efficiency for a zigzag baffle separator.

A zigzag baffle section is shown in Figure 27. The gas flow pattern in a baffle section is too intricate to be described as a series of gentle bends. The model used by Calvert et al. to characterize the flow includes the effects of turbulent mixing. Calvert's model leads to the following expression for collection efficiency:

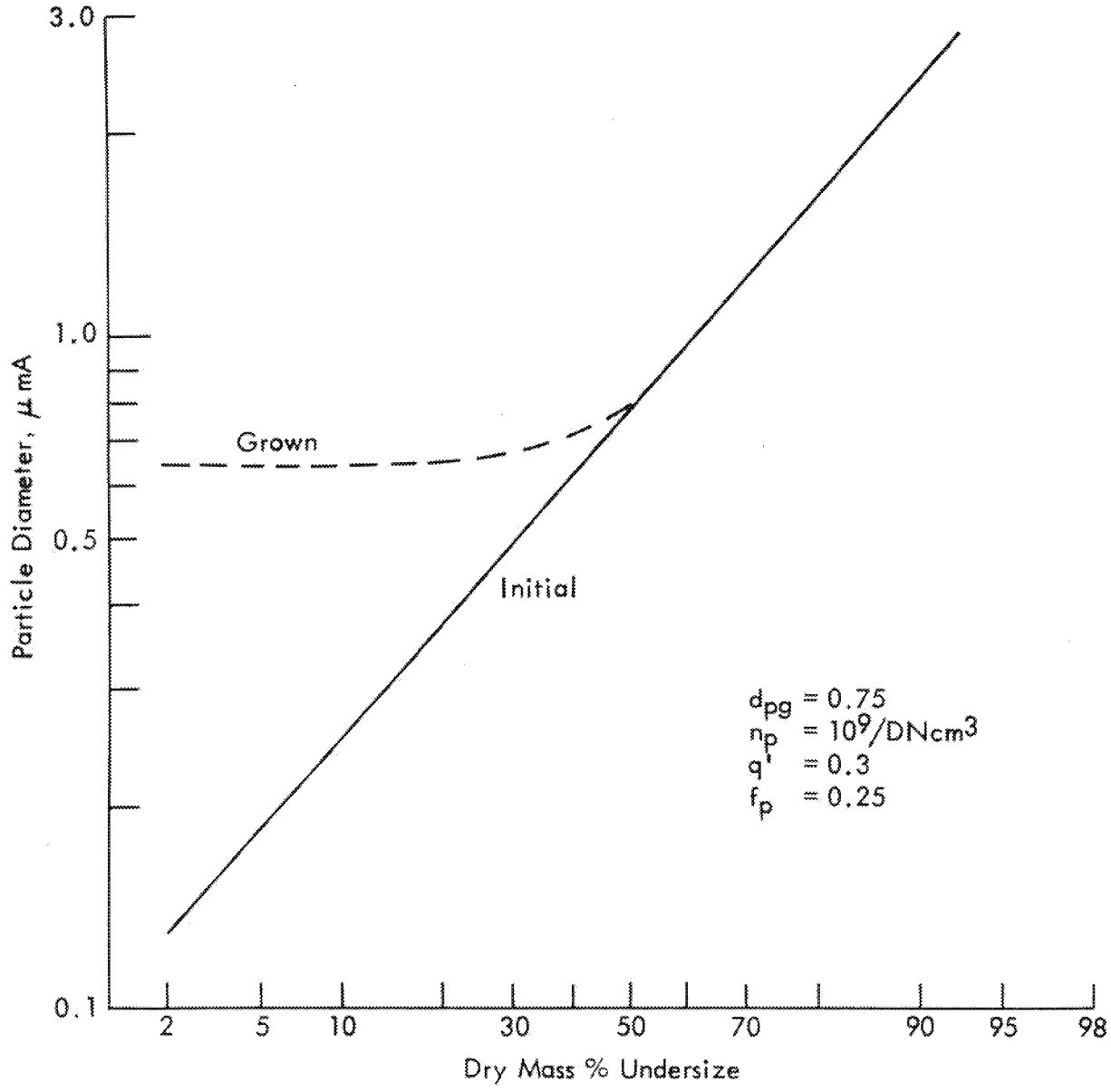



Figure 26. Particle size distribution before and after condensation.[3/]

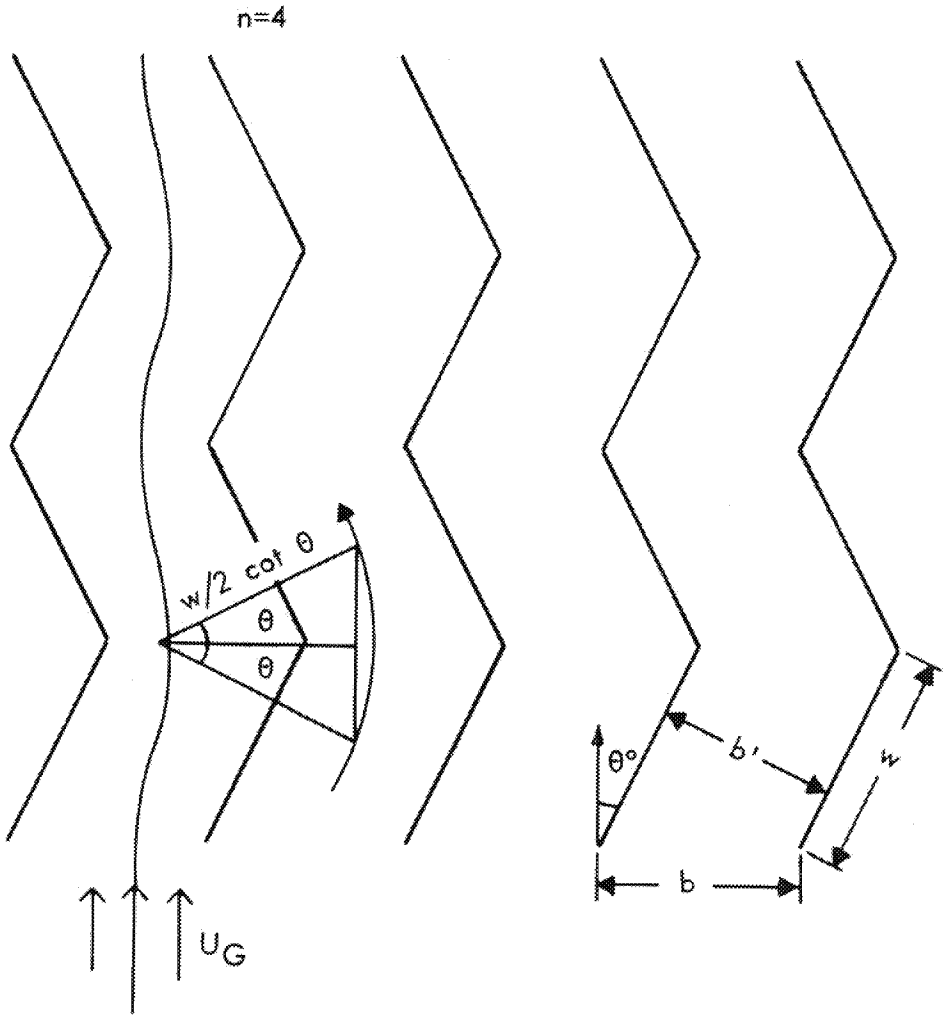



Figure 27. Continuous zigzag baffles.

$$E = 1 - \exp\left[-\frac{u_{tc}\, n w_b\, \theta}{57.3\, U_G\, b \tan\theta}\right] \qquad (5.3)$$

where $E$ = collection efficiency, fraction

$u_{tc}$ = drop (or particle) terminal centrifugal velocity, in the normal direction, cm/sec

$U_G$ = superficial gas velocity, cm/sec

$n$ = number of bends or rows

$\theta$ = angle of inclination of the baffle to the flow path, degrees

$w_b$ = width of baffle, cm

$b$ = spacing between two consecutive baffles in same row, cm

Particle penetration (1-E) is frequently used to describe performance, and in terms of this concept Eq. (5.3) becomes

$$1 - E = P = \exp\left[-\frac{u_{tc}\, n w_b \theta}{57.3\, U_G\, b \tan\theta}\right] \qquad (5.4)$$

The drop (or particle) terminal centrifugal velocity can be determined by performing a force balance on the drop. The result is

$$u_{tc} = \left[\frac{4}{3}\frac{d_p \rho_p a}{C_D \rho_g}\right]^{0.5} \qquad (5.5)$$

where $d_p$ = particle diameter, cm

$\rho_p$ = particle density, g/cm$^3$

$a$ = acceleration due to centrifugal force, cm/sec$^2$

$C_D$ = drag coefficient

$_g$ = gas density, g/cm$^3$

If the drop (or particle) Reynold's number is low ($N_{Re,D} < 0.1$), Stokes' law applies. For this condition, the drag coefficient is given by

$$C_D = \frac{24}{N_{Re,D}} \tag{5.6}$$

where $N_{Re,D}$ = drop Reynolds number

$$= \frac{d_p\ u_{tc}\ \rho_g}{\mu_g}$$

where $_g$ = gas viscosity, poise

By combining Eqs. (5.5) and (5.6), we obtain

$$u_{tc} = \frac{d_p^2\ \rho_p\ a}{18\ \mu_g} \tag{5.7}$$

The acceleration due to centrifugal force is defined by the following equation.

$$a = \frac{2\ (U_G')^2}{w_b\ \cot\ \theta} = \frac{2\ U_G^2\ \sin\ \theta}{w_b\ \cos^3\ \theta} \tag{5.8}$$

where $U_G'$ = actual velocity between baffles, cm/sec

Substitution of Eqs. (5.7) and (5.8) into Eq. (5.3) gives the following expression for collection efficiency:

$$E = 1 - \exp\left[-\frac{d_p^2\ \rho_p\ U_G\ n\ \theta}{(515.7)\ \mu_g\ b\ \cos^2\ \theta}\right] \tag{5.9}$$

Equation (5.9) expresses the collection efficiency in terms of the baffle design parameters and the emission stream properties, and the equation can be used to predict the performance of baffle systems.

5.1.2.1 Influence of Baffle Design Parameters on Performance - The effect of baffle design parameters on performance can be assessed setting $d_p$, $\rho_p$, and $U_G$ as constants in Eq. (5.9) and varying $n$, $\theta$, and $b$. Table 26 illustrates the impact of changing baffle design parameters on performance for the following representative values of the emission parameters

$d$ = 60 $\mu$ ($6 \times 10^{-3}$ cm)

$\rho_p$ = 2 g/cm$^3$

$U$ = 300 cm/sec

$\mu_g$ = $1.8 \times 10^{-4}$ poise

TABLE 26. INFLUENCE OF BAFFLE DESIGN PARAMETERS ON PERFORMANCE

| No. of rows n | Distance between baffles b (cm) | Angle of baffle inclination $\theta$ (degree) | Penetration (P) | Efficiency (E) |
|---|---|---|---|---|
| 1 | 5 | 15 | 0.47 | 0.53 |
| | 5 | 30 | 0.16 | 0.84 |
| | 5 | 45 | 0.015 | 0.985 |
| | 7 | 45 | 0.05 | 0.95 |
| | 10 | 45 | 0.12 | 0.88 |
| 2 | 5 | 15 | 0.22 | 0.78 |
| | 5 | 30 | 0.024 | 0.976 |
| | 5 | 45 | $2 \times 10^{-4}$ | 0.9998 |
| 3 | 5 | 15 | 0.11 | 0.89 |
| | 5 | 30 | 0.004 | 0.996 |
| | 5 | 45 | $3.4 \times 10^{-6}$ | 100 |

Assumptions: dp = 60 microns

$\rho p = 2$ g/cm$^3$

Ug = 300 cm/sec

$\mu g = 1.8 \times 10^{-4}$ poise

Inspection of Table 26 shows that the angle of inclination has the most dramatic influence on particle penetration for the assigned gas and particulate parameters. However, because the exponential term in Eq. (5.9) has a complex dependence on $d_p$ and $\theta$, the relative importance of n and $\theta$ on performance will be a function of particle size. This point is shown by comparison of Figures 28 through 30. As the particle size decrease, the importance of n increases relative to the angle $\theta$. These figures also illustrate that, in general, the baffles do not efficiently remove 10 $\mu$m particles, but may effectively remove 100 $\mu$m particles depending on angle of inclination and number of rows.

5.1.2.2 Influence of Particle and Gas Properties on Performance - If one wishes to examine the influence of particle and gas properties on the performance, a fixed baffle design is chosen. Table 27 illustrates the strong effect of the particle size and gas velocity on performance.

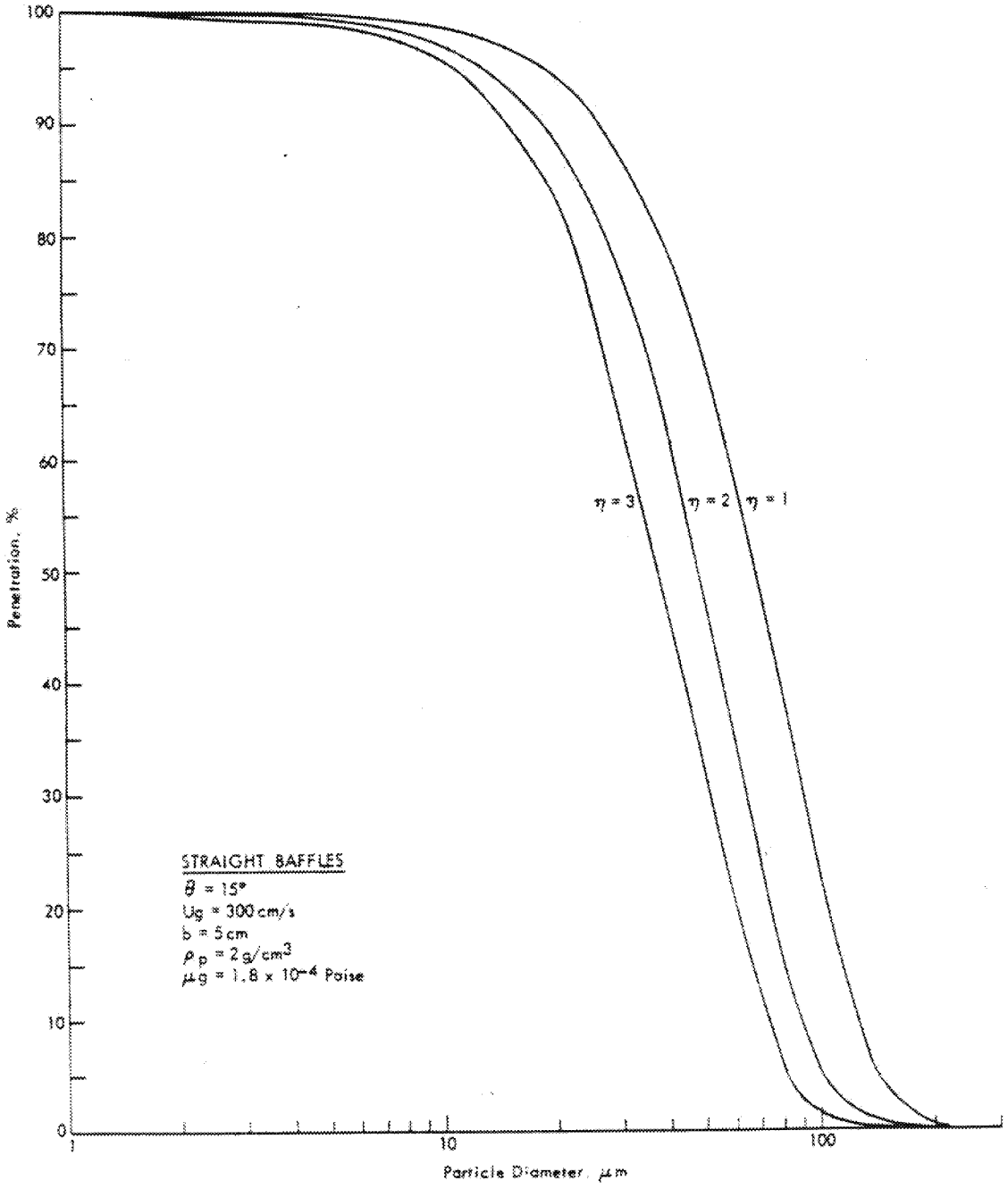



Figure 28. Penetration versus particle size, for 15 degree baffles.

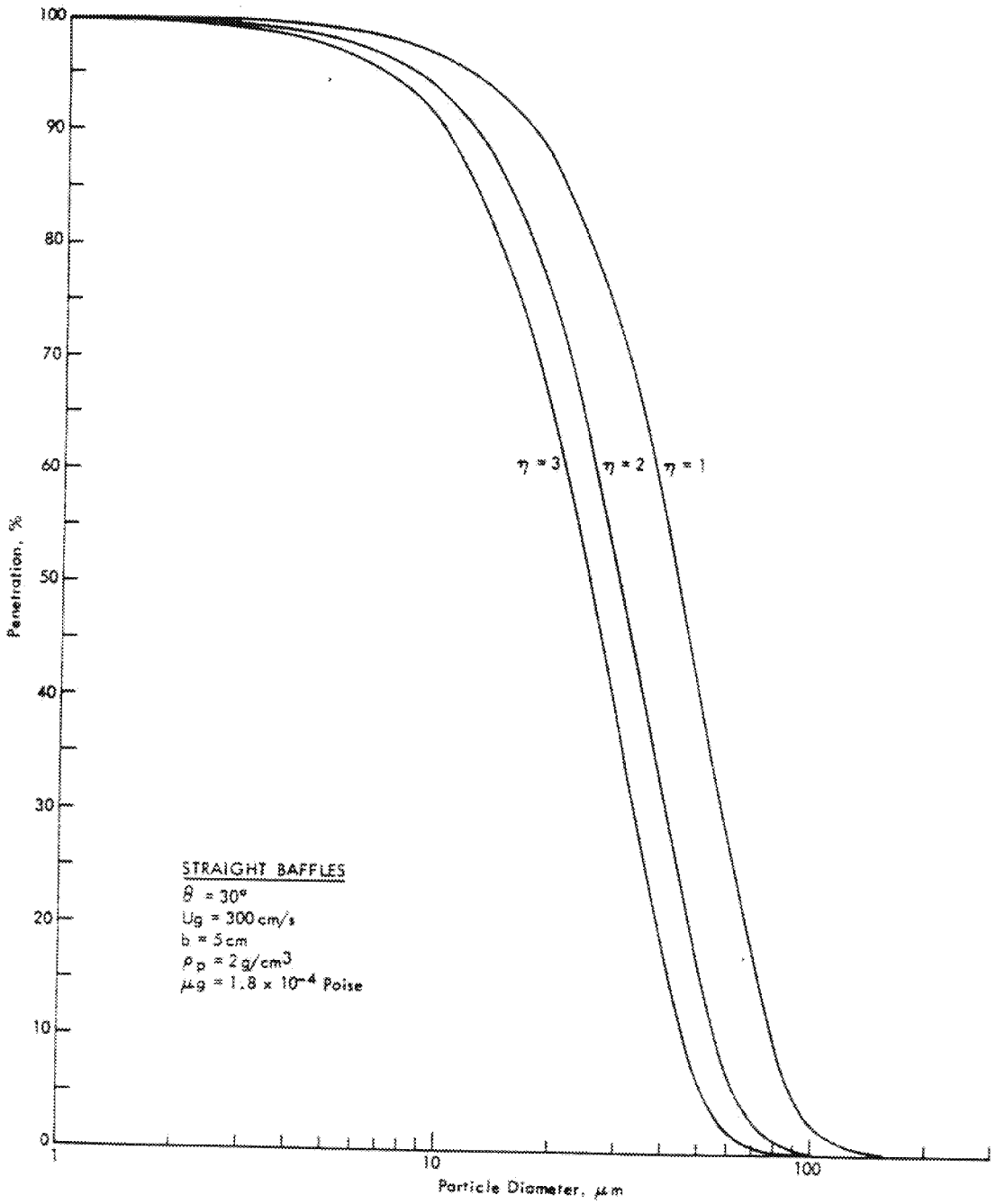



Figure 29. Penetration versus particle size, for 30 degree baffles.

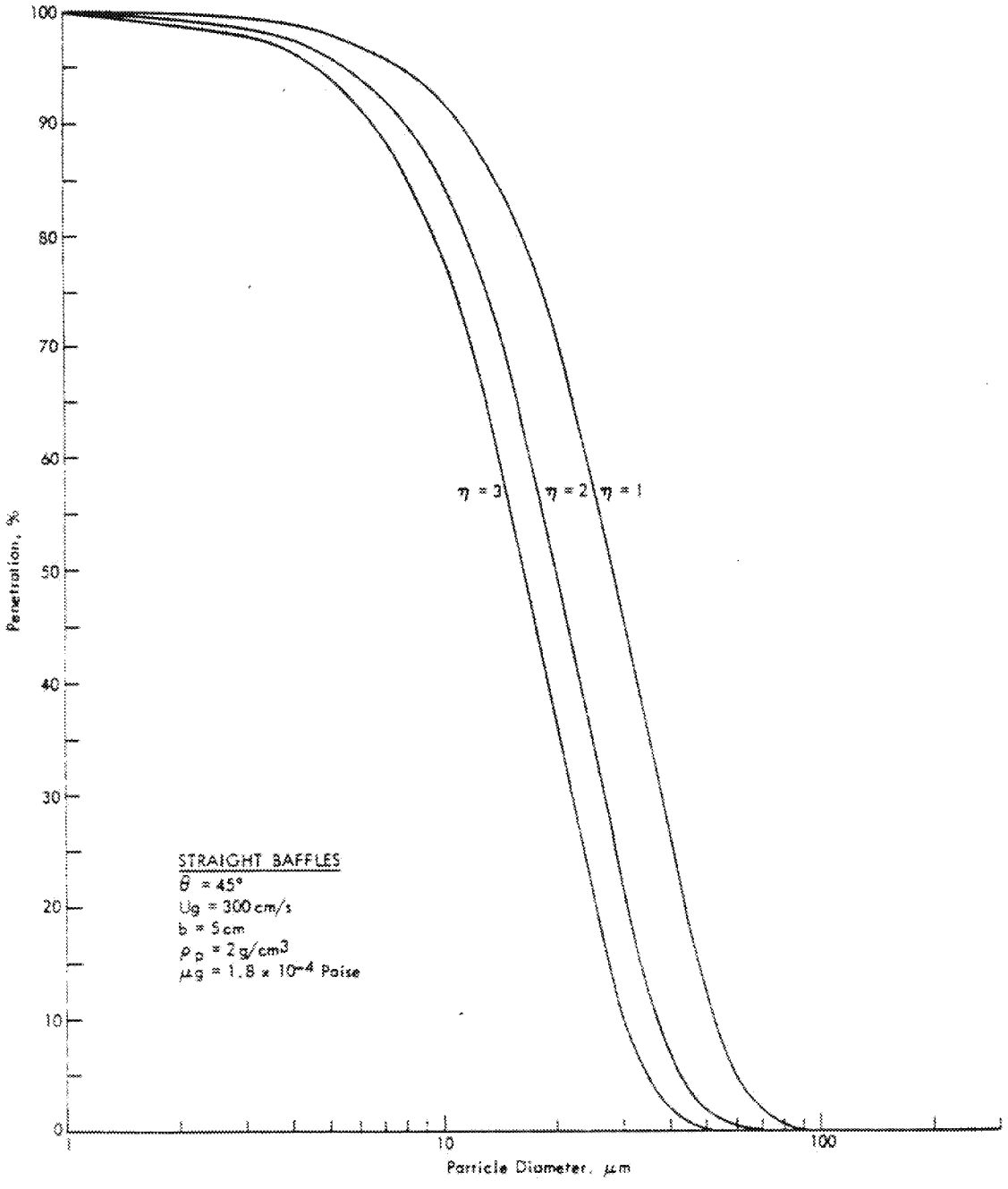



Figure 30. Penetration versus particle size, for 45 degree baffles.

TABLE 27. INFLUENCE OF PARTICLE AND GAS PROPERTIES ON PERFORMANCE

| Particle Size dp ($\mu$m) | Gas Velocity $U_G$ (cm/sec) | Particle Density $\rho$ (g/cc) | Penetration (P) | Efficiency (E) |
|---|---|---|---|---|
| 20 | 300 | 2 | 0.71 | 0.29 |
| 40 | 300 | 2 | 0.26 | 0.74 |
| 60 | 100 | 2 | 0.37 | 0.63 |
| 60 | 300 | 1 | 0.22 | 0.78 |
| 60 | 300 | 2 | 0.05 | 0.95 |
| 60 | 500 | 2 | 0.007 | 0.993 |

Assumptions: $n = 1$

$b = 7$ cm

$\theta = 45°$

$\mu g = 1.8 \times 10^{-4}$ poise

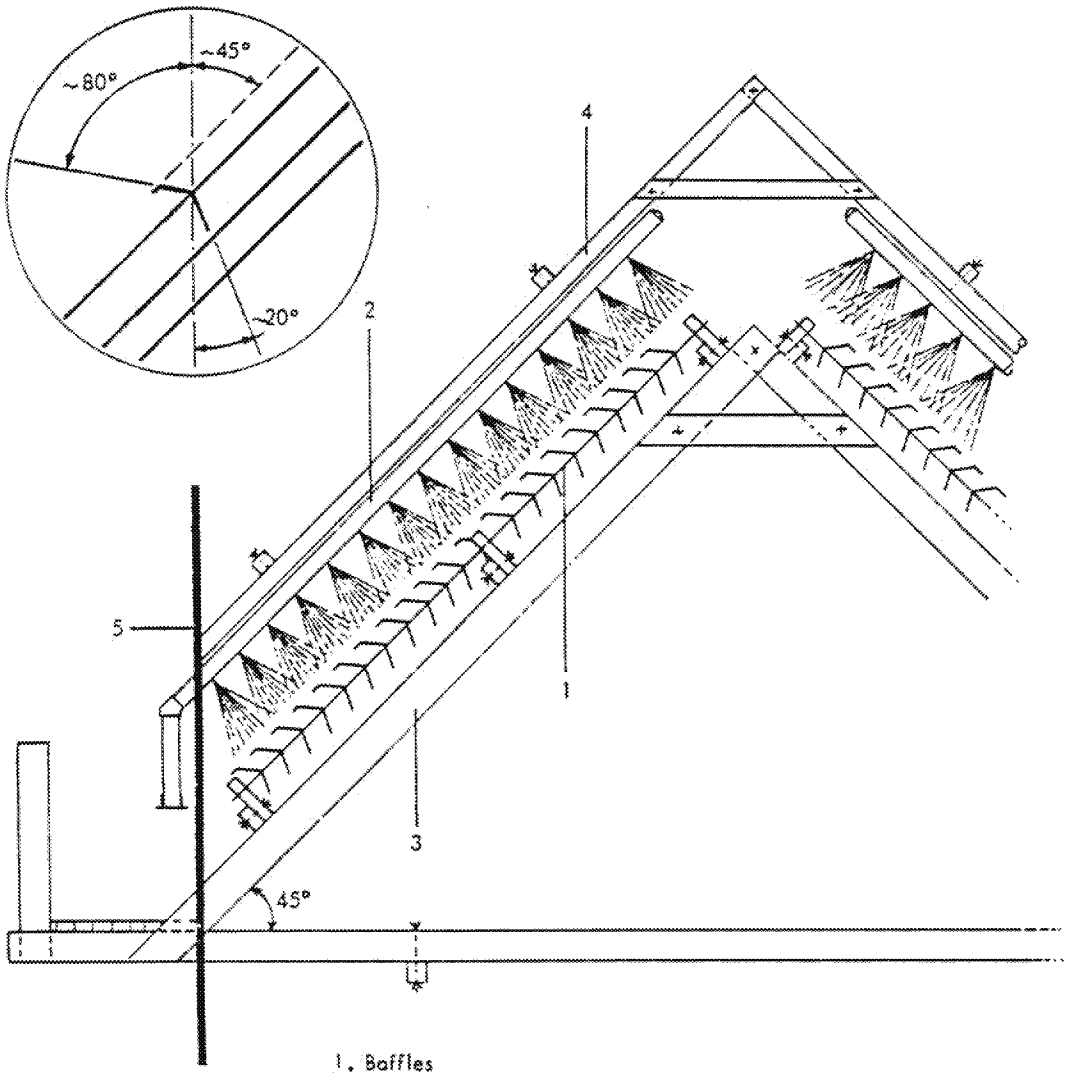
5.1.2.3 Special Baffle Designs - The most common baffle design is the zigzag with various numbers of passes. The Carl Still Company has developed a baffle design which incorporates the advantages of multiple passes, but uses only a single row of baffles. Figures 31 and 32 illustrate the baffle used in this system. As shown in Figure 32, the baffle incorporates three changes in direction with varying angles at each change of direction.

Equation (5.9) can be used to estimate the performance of this system by treating each bend as a separate entity and then computing the total penetration for all bends (i.e., treat the individual bends in a series manner). Table 28 presents the estimated performance of this system for the following operation conditions of Armco's Middletown No. 3 unit.

$U_g = 267$ cm/sec

$b = 12$ cm

$\rho = 2$ g/cc




1. Baffles
2. Flushing Lines
3. Supporting Structure for the Baffles
4. Supporting Structure for the Flushing Pipes
5. Quench Tower Wall

a/ Adapted from reference 8.

Figure 31. Firma Carl Still baffles, end view.a/

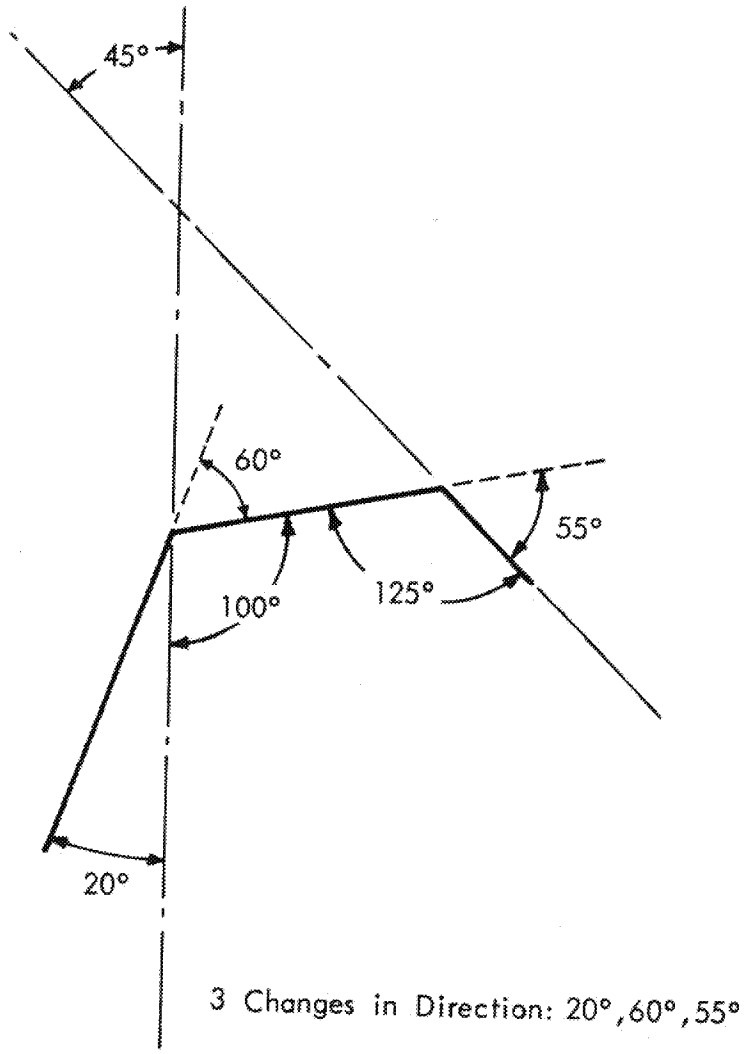



Figure 32. Diagram of Carl Still baffle angles.

TABLE 28. ESTIMATED PERFORMANCE OF FIRMA CARL STILL UNIT AT ARMCO'S MIDDLETOWN NO. 3 UNIT

| $d_p$ (μ) | Penetration | | | | Overall efficiency |
|---|---|---|---|---|---|
| | Bend 1 | Bend 2 | Bend 3 | Overall | |
| 20 | 0.96 | 0.63 | 0.73 | 0.44 | 0.56 |
| 40 | 0.84 | 0.16 | 0.28 | 0.036 | 0.964 |
| 60 | 0.68 | 0.016 | 0.056 | 0.0006 | 0.9994 |

Like Table 28, Eq. (5.9) has been used to prepare Figure 33 showing the effect of particle size on efficiency. Comparison of Figure 33 with Figure 30 indicates that the Carl Still baffle design yields about the same efficiency as three rows of 45 degrees baffles.

In conclusion, this theoretical evaluation of particulate removal by baffles shows that they may be highly efficient for large particles but, as expected, the efficiency decreases rapidly for particles $< 10$ $\mu$m.

### 5.1.3 Comparison of Theoretical Predictions With Available Test Data

Very little data are available which can be used for checking the validity of the theoretical prediction methods described in the preceding section and of more concern are the measurement techniques used to obtain that data which are available (i.e., particle size distribution). For instance, Figures 28 through 30 indicate that a single row of baffles should have high efficiency of removal for particles above 100 $\mu$m, but work reported by Jackson and Waple[38] for 20 degrees baffles and average velocity of 3 to 5 m/sec shows only about 40% removal for the mean size of 250 $\mu$m and only about 60% removal for particles above 600 $\mu$m. This low removal efficiency for such large particles is highly suspect. In fact, the authors noted that the data may not be sufficient for calculation of efficiency by size.

Much of the other data, although sparse, does indicate that the average particle size of uncontrolled quench tower emissions is relatively large. Some English data note 85% of the particles above 76 $\mu$m and other mass emission tests note that much of the "catch" occurred in the sampling probe, presumably being particles above 10 $\mu$m.

On the other hand, emissions tests at the outlet of the baffled tower (i.e., Lorain)[52] show that 72% was caught in the probe, which is believed to represent a size range of 2.8 to 10.2 $\mu$m, and less than 20% was caught in the cyclone on the front of the probe (i.e., particles above 10.2 $\mu$m) or in the final filter. Therefore, if the average size of the uncontrolled emissions is large, as indicated earlier, this seems to verify the expectation that they are efficiently removed by baffles.

Work by Fullerton[26] (using greased plate sampling) is pertinent to the theoretical prediction because it involved sampling before and after installation of baffles. It showed that one row of 20 degrees baffles reduced emissions by 60% whereas 45 degrees baffles reduced emissions by 85%. Referring to Figure 30, 85% removal for 45 degrees baffles would indicate an average inlet particle size of $\sim 50$ $\mu$m. Using this size in Figure 28, for 15 degrees baffles, shows a removal efficiency of 30 to 40%. Considering the uncertainties involved, Fullerton's data appear to show that the theoretical predictions are reasonable.

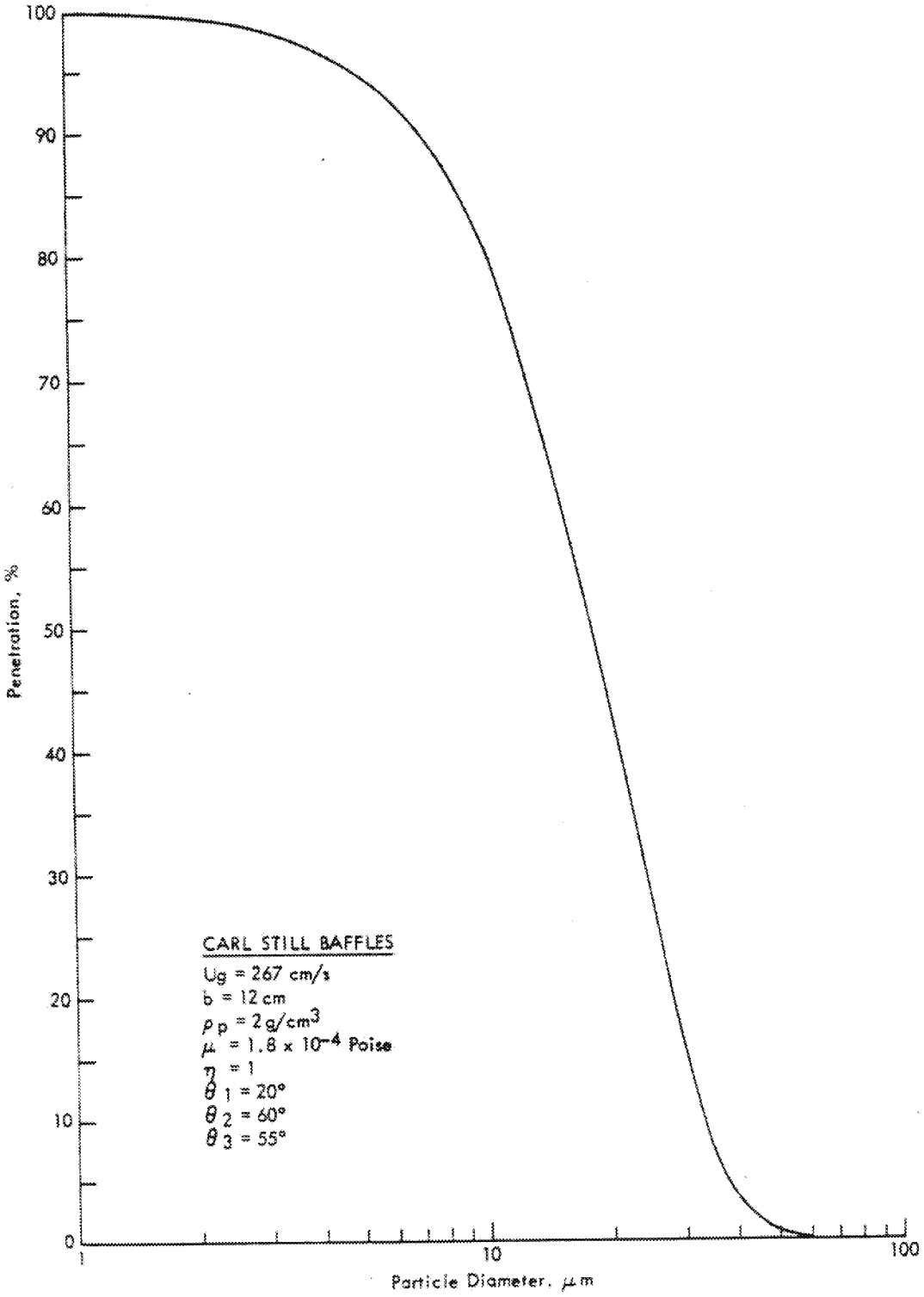



Figure 33. Penetration versus particle size for Carl Still baffles.

## 5.2 NEED FOR MORE COMPREHENSIVE THEORETICAL PREDICTION METHODS

The previous section presented development of an equation (Eq. (5.9)) that could be used to predict removal efficiency for various size particles in a quench tower having a specific baffle configuration, when the superficial gas velocity is known. However, the test data discussed earlier showed that gas velocity varies with time and location in the tower. It is also likely that the mass concentration and particle size distribution themselves vary with time during each quench. Therefore, if the variability in these parameters could be determined, a more accurate and realistic estimate of baffle performance (removal efficiency) could be carried out using Eq. (5.9) in an appropriate computer model.

A specific quench tower could be divided into several sections and within each section an algorithm could be developed and used to express the variation in velocity, concentration and particle size as a function of time. Then for each time segment, Eq. (5.9) would be used to compute removal efficiency in each section of the tower to yield total removal efficiency for all sections. Integration of total removal efficiency over the entire time period of the quench would then show total mass removed by the baffles. This would certainly be a more accurate approach than that using average values for velocity, concentration, and particle size. It is estimated that development of such a model would require about 2,000 man-hours, assuming that data were available from which suitable algorithms could be derived. In this regard, the available test data do contain some information on variations in velocity with time and location. There are also data available on variations in mass concentration with location, but not with time. Perhaps more importantly, there may not be any data available on variability of particle size distribution with time. If these data are not available it would have to be obtained in order to develop a computer model. If such a model could be developed, it would be useful in assessing emissions from quench towers, even if only some average data were available for those towers, and in assessing performance of different baffle designs. However, any such model would only be as good as the information used in its development, including any particle size data. Measurement of particle size in quench towers is quite difficult and use of such data in a computer model, or in Eq. (5.9), may have to await development of better methods for determining size distribution. At present, the available data on particle size distribution before and after any control system (i.e., baffles) are very limited so it is difficult to verify any model. Therefore, it is difficult to assess even the relative differences in the effectiveness of different control methods.

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# APPENDIX A

## SUMMARY OF QUENCH TOWER INFORMATION OBTAINED DURING PLANT VISITS

Six site visits were carried out as one part of the investigation into coke quench tower operation. Table A-1 presents a summary of the data obtained in regard to the quench towers inspected in these plants.

## TABLE A-1. SUMMARY OF QUENCH TOWER CHARACTERISTICS OBTAINED FROM SITE VISITS

| Company - Location | Battery Served (No.) | Quench Tower Construction Material | Tower Cross Section ($m^2$ at highest point) | Tower Height[a/] | Tower Shape | Tower Orientation | Quench Method |
|---|---|---|---|---|---|---|---|
| Alabama By-products Corp. - Birmingham, AL | 1 | ss | 56.4 | 54.5 | rec | o | css |
| | 2 | ---same tower--- | | | | | |
| | 5,6 | bk | 76.6 | 17.1 | rec | a | css |
| Armco Steel Corp. - Middletown, OH | 3 | ss | 54.7 | 37.4 | rec | o | css |
| | 2 | bk | 14.3 | 30.0 | cir | a | css |
| Inland Steel Co. - East Chicago, IN | 6,7 | bk | 18.7 | 31.4 | cir | a | css |
| | 10 | ---same as above--- | | | | | |
| | 8,9 | ---same as above--- | | | | | |
| | C | bk | 49.2 | 31.4 | cir | a | css |
| | 11 | ---same as above--- | | | | | |
| Jones and Laughlin Steel - Pittsburgh, PA | P1, P2, P3N | wd | 107 | 18.3 | rec | a | css |
| | P3S, P4 | wd | 20.9 | 30.5 | rec | a | css |
| Shenango, Inc. - Neville Is., NY | all | bk | 100 | 17.1 | rec | a | css |
| U. S. Steel Corp. - Clairton, PA | 1,2,3 | wd | 20.9 | 30.5 | rec | a | LM |
| | 12A | bk | 12.3 | 45.7 | cir | a | LM |
| U. S. Steel Corp. - Fairfield, AL | 2 | wd | 61.9 | 37.1 | rec | o | css |
| | 6 | bk | 124 | 14.9 | rec | a | LM |

a/ (m, perpendicular distance from quench car rails to tower's highest point.)

Legend:
- ss = stainless
- wd = wood
- bk = brick
- rec = rectangular
- cir = circular, with a small decrease in diameter at the top
- a = above quench car
- o = offset
- css = conventional spray system
- LM = Lo-No

## TABLE A-1. (continued)

| Company - Location | Coke Transport Method | Coke/Quench (Mg) | Quench Water Discharged/Quench ($10^2$ ℓ) | Quench Water Discharged/Mg Coke ($10^2$ ℓ) | Evaporative Loss/Quench ($10^2$ ℓ) | Evaporative Loss/Mg Coke ($10^2$ ℓ) | Primary Source of Quench Water |
|---|---|---|---|---|---|---|---|
| Alabama By-products Corp. - Birmingham, AL | cc | 17.2 | 265 | 15.4 | ~70.9 | ~4.12 | ww, rw |
| | -same tower- | 6.3 | 132 | 21.0 | ~26.0 | ~4.12 | -same as above- |
| | cc | 10.9 | 189 | 17.3 | ~44.9 | ~4.12 | ww, rw |
| Armco Steel Corp. - Middletown, OH | ost | 19.1 | 379 | 19.8 | 126 | 6.60 | rw |
| | cc | 11.4 | 341 | 29.9 | 73.8 | 6.47 | rw |
| Inland Steel Co. - East Chicago, IN | cc | ~9.1 | ~378 | ~41.5 | ~57.0 | 6.26 | lw |
| | ---------- | ---------- | -same as above- | ---------- | ---------- | ---------- | ---------- |
| | ---------- | ---------- | -same as above- | ---------- | ---------- | ---------- | ---------- |
| | ls | - | - | - | - | - | lw |
| | -same as above- | - | - | - | - | - | lw |
| Jones and Laughlin Steel - Pittsburgh, PA | cc | 10.2 | - | - | - | - | - |
| | cc, ls | 10.2 | - | - | - | - | - |
| Shenango, Inc. - Neville Is., NY | cc | ~13.6 | ~151 | ~11.1 | ~75.7 | 5.57 | rw |
| U. S. Steel Corp. - Clairton, PA | cc | - | - | ~5.5 | - | - | rw |
| | cc | - | - | ~5.5 | - | - | rw |
| U. S. Steel Corp. - Fairfield, AL | cc | 21.8 | 602 | 27.6 | 151 | 6.93 | - |
| | cc | 10.0 | 246 | 24.6 | 53.0 | 5.30 | - |

Legend: cc = conventional car
ls = one spot car
ost = Osterfeld car
rw = river water
lw = lake water
ww = well water

(continued)

## TABLE A-1. (continued)

| Company - Location | Plant Wastewater Included as Makeup | Mist Eliminator in Use | Construction Material for Baffles | Height of Mist Eliminator (m) | Baffle Inclination from a Vertical Axis | Baffle Configuration | Perpendicular Distance Between Baffles (cm) | Duration of Quench (sec) |
|---|---|---|---|---|---|---|---|---|
| Alabama By-products Corp. - Birmingham, AL | n | y | wd | 21.8 | 45° | 1r | ~5.3 | 190 |
| | ---------- | ---------- | ---------- same as above ---------- | | | | | 70 |
| | n | y | wd | 15.0 | 45° | 1r | ~5.1 | 170 |
| Armco Steel Corp. - Middletown, OH | n | y | pl | ~30.0 | 45° | af, s | ~12.0 | 135 |
| | n | y | ss | 28.8 | 20° | 2r, o | 9.7 | 105 |
| Inland Steel Co. - East Chicago, IN | n | y | wd | 30.2 | 45° | af | ~8.0 | 120 |
| | ---------- | ---------- | ---------- same as above ---------- | | | | | |
| | ---------- | ---------- | ---------- same as above ---------- | | | | | |
| | n | y | wd | - | 15° | d | ~10.0 | - |
| | n | y | wd | - | 15° | d | ~10.0 | - |
| Jones and Laughlin Steel - Pittsburgh, PA | - | y | wd | ~16 | 45° | 1r | - | - |
| | - | y | wd | ~27 | 45° | af | - | - |
| Shenango, Inc. - Neville Is., PA | y | y | wd | ~15 | 20° | 2r | ~8.9 | 120 |
| U. S. Steel Corp. - Clairton, PA | - | y | wd | ~6 | 45° | 1r | - | ~80 |
| | - | y | wd | ~6 | 45° | 1r | - | ~80 |
| U. S. Steel Corp. - Fairfield, AL | n | y | pl | 27.0 | 45° | af, s | ~12.0 | 95 |
| | n | y | wd | 7.2 | 45° | 1r | ~18.0 | 90 |

Legend:
- y = yes
- n = no
- wd = wood
- ss = stainless steel
- pl = plastic
- 1r = one horizontal row
- 2r = two horizontal rows
- 2r,o = two opposed horizontal rows
- af = A-frame
- af,s = A-frame, Carl Still Design
- d = dome